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# SOLID PROPELLANT TEST EVALUATION OF A WATER-COOLED NOZZLE


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A. A. BASSONI


TECHNICAL REPORT AFRPL-TR-69-75

APRIL 1969

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# SOLID PROPELLANT TEST EVALUATION OF A WATER-COOLED NOZZLE

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A.A. BASSONI

## FOREWORD

The nozzle test program described was performed by the Air Force Rocket Propulsion Laboratory (AFRPL). Project direction was provided by the Motor Component Development Branch under Project SRHDE, 305903AMG. This work was performed in support of NASA Contract NAS 3-10302 with the Aerojet-General Corporation and covered the period 15 October 1967 to 1 March 1969. Facility buildup costs were covered by NASA under Purchase Request 248639. The nozzle tested was the last of a series of three to be fired at AFRPL.

Project Engineers for the test program were Mr. James Pelloch, NASA, Lewis Research Center; Mr. V. R. Stubbs, Aerojet-General Corporation; and Lt. David R. Zorich and Mr. Attilio A. Bassoni, AFRPL (RPMCH).

Individuals participating in this test program and in the preparation of this report were: Mr. Tully Becker and Mr. Hugh Jamison, Instrumentation, Technical Support Division (RPF); Mr. Thomas Glaze, Technical Support Division (RPF); Mr. William J. Sando, Test Branch, Solid Rocket Division (RPMT); and Mr. Irving Gulick, Data Reduction, Computing and Software, Inc.

This report has been reviewed and approved.

CHARLES R. COOKE
Chief, Solid Rocket Division
Air Force Rocket Propulsion Laboratory

# ABSTRACT

The objective of this test program was to evaluate the feasibility of using a water-cooled nozzle on large solid propellant motors. The coolant requirement for this test was 1200 gal/min water flow rate with an inlet coolant pressure of 850 psi. The flow was reduced during the test with a minimum water flow rate of 560 gal/min. The nozzle performed successfully with no indication of tube burnthrough or film boiling occurring. Test duration was 62 seconds at an average chamber pressure of 380 psi. Results of this test indicated the entire system operated satisfactorily at maximum operating conditions.

TABLE OF CONTENTS


| Section | | Page |
|---|---|---|
| I. | INTRODUCTION | 1 |
| | A. Objective | 1 |
| | B. Motor Specifications | 2 |
| | C. Nozzle Design | 2 |
| | D. Test Program | 2 |
| | E. Test Results | 3 |
| II. | GAS-PRESSURIZED COOLANT FACILITY DESCRIPTION | 5 |
| III. | CHECKOUT TEST RESULTS | 6 |
| IV. | NOZZLE DESCRIPTION | 8 |
| | A. Nozzle Design | 8 |
| | 1. Method of Analysis | 9 |
| | 2. Discussion of Results | 10 |
| | 3. Conclusions and Recommendations | 10 |
| V. | TEST FIRINGS AND RESULTS | 21 |
| VI. | CONCLUSIONS | 31 |
| REFERENCES | | 32 |
| APPENDIX - CHECKOUT PROCEDURES | | 33 |
| DISTRIBUTION | | 39 |
| FORM 1473 | | 45 |

## TABLES

| Table | | Page |
|---|---|---|
| I. | Checkout of Water-Flow Results | 7 |
| II. | Nozzle Instrumentation Checklist | 16 |


## ILLUSTRATIONS

| Figure | | Page |
|---|---|---|
| 1. | Nozzle Schematic View | 4 |
| 2. | Coating Development Program, Effect of Coolant Flow Reduction | 11 |
| 3. | Cooling Development Program, Wall Temperatures | 12 |
| 4. | Coating Location | 14 |
| 5. | Nozzle Installation Showing Thermocouple Installation (Prefire) | 18 |
| 6. | Prefire Exit Cone Showing Coating Locations | 19 |
| 7. | Close-Up of Nozzle Throat Showing Coating Gradations (Prefire) | 20 |
| 8. | Water Flow Rate and Percent Open W-4 versus Time | 22 |
| 9. | Postfire Throat Region Showing Alumina Buildup | 23 |
| 10. | Postfire Exit Cone Showing Alumina Buildup | 24 |
| 11. | Postfire View of Entrance Section and Aft Closure Showing Erosion Patterns | 25 |
| 12. | Postfire Close-Up Showing Ablative Sleeve Erosion and Nozzle Throat | 26 |
| 13. | Coolant Inlet Temperature versus Time | 28 |
| 14. | Coolant Outlet Temperature versus Time | 29 |
| 15. | System Pressures versus Time | 30 |

## SECTION I

## INTRODUCTION

This report is a compilation of data provided by the third in a series of three AFRPL Minuteman motor tests of an $Al_2O_3$-based thermal-barrier-coated Second Stage Titan II, water-cooled nozzle. The nozzle was modified and coated by the Aerojet-General Corporation under NASA Contract NASA 3-10302. Motor and gas-pressurized water coolant facility performance are discussed, as well as the nozzle test-firing data.

### A. OBJECTIVE

The objective of this test was to demonstrate a water-cooled nozzle concept for solid propellant motors. NASA Contract NAS 3-10302, "Development of a Thermal Barrier Coating for Use on a Water-Cooled Nozzle of a Solid Propellant Rocket Motor," was initiated on 3 July 1967 for the purpose of developing a reliable $Al_2O_3$-based, thermal-barrier coating that can be applied to large water-cooled nozzles, and which will provide a substantial reduction of heat flux to the coolant. The program was performed in two tasks as follows:

TASK I - MATERIALS AND PROCESS SELECTION

Analytical selection of candidate $Al_2O_3$ systems and subsequent laboratory evaluation to determine the order of preference for test firing were performed in this task.

TASK II - DESIGN AND FABRICATION

Design and fabrication of three nozzles for subscale test-firing were performed. Titan II Second Stage combustion chambers were used as single nozzles for Wing I Minuteman Second Stage motors. A high-pressure water-flow facility (described in Reference 1) was utilized to supply the water-cooled nozzle. The objectives were achieved by:

(1) Design and fabrication of the water-cooled nozzle.

(2) Prefire test of the water-coolant facility utilizing the nozzle to be test-fired, to determine the minimum water flow rates and pressures.

(3) Posttest evaluation of the rocket nozzle, inlet ablative regression, and nozzle performance.

## B. MOTOR SPECIFICATIONS

The motor used for this test was a Wing I, Second Stage Minuteman motor. This motor contains a conventional, cured, aluminized propellant grain. It was fired horizontally. The theoretical flame temperature was 5700°F at a nominal chamber pressure of 400 psi. A specially designed aft closure insulated with Gen Gard V-61 trowelable rubber was the only modification made to the existing Minuteman motor.

## C. NOZZLE DESIGN

The nozzle used in this test was provided by the Aerojet-General Corporation under NASA Contract NAS 3-10302 and incorporated a 9.1-inch-throat diameter, regeneratively cooled, Second Stage Titan II combustion chamber. This nozzle utilized an $Al_2O_3$-base coating. In order to reduce the thermal flux induced upon the coolant tubes, an ablative sleeve consisting of tape-wrapped carbon cloth phenolic and silica phenolic was placed between the water inlet manifold and the throat section. The nozzle design is shown in Figure 1.

## D. TEST PROGRAM

This firing was the last in a series of three to be conducted at AFRPL. The desired test parameters were a 60-second duration, 5700°F flame temperature, and nominal chamber pressure of 400 psia. Water-coolant requirements were 1200 gal/min water flow with an inlet pressure of 850 psi. Water flow rates were reduced during the couse of firing to minimize collant requirements. The third demonstration firing was conducted on 19 February 1969. The contractural testing is now completed and the final program report will be distributed by Aerojet-General in March 1969.

## E. TEST RESULTS

The preliminary test results indicate that the nozzle performed quite satisfactorily and showed no burnout during the entire 63-second test firing. Large deposits of solidified $Al_2O_3$ from the exhaust covered the entire surface of the exit cone. Samples of this material were analyzed both chemically and metallurgically. The test duration was 63 seconds with nominal chamber pressure of 380 psi. Water flow rates showed an initial 1200 gal/min with an inlet pressure of 830 to 850 psi. The flow was reduced to a minimum of 560 gal/min (inlet pressure of 725) during motor action time. The alumina base coating in the throat region was intact with little removal by particle impingement. The ablative section was in excellent condition and exhibited minimal regression. (No measurements were available for this report.) The water-cooled nozzle was successfully test-fired on a solid propellant motor, and exhibited no film boiling or tube burnthrough.

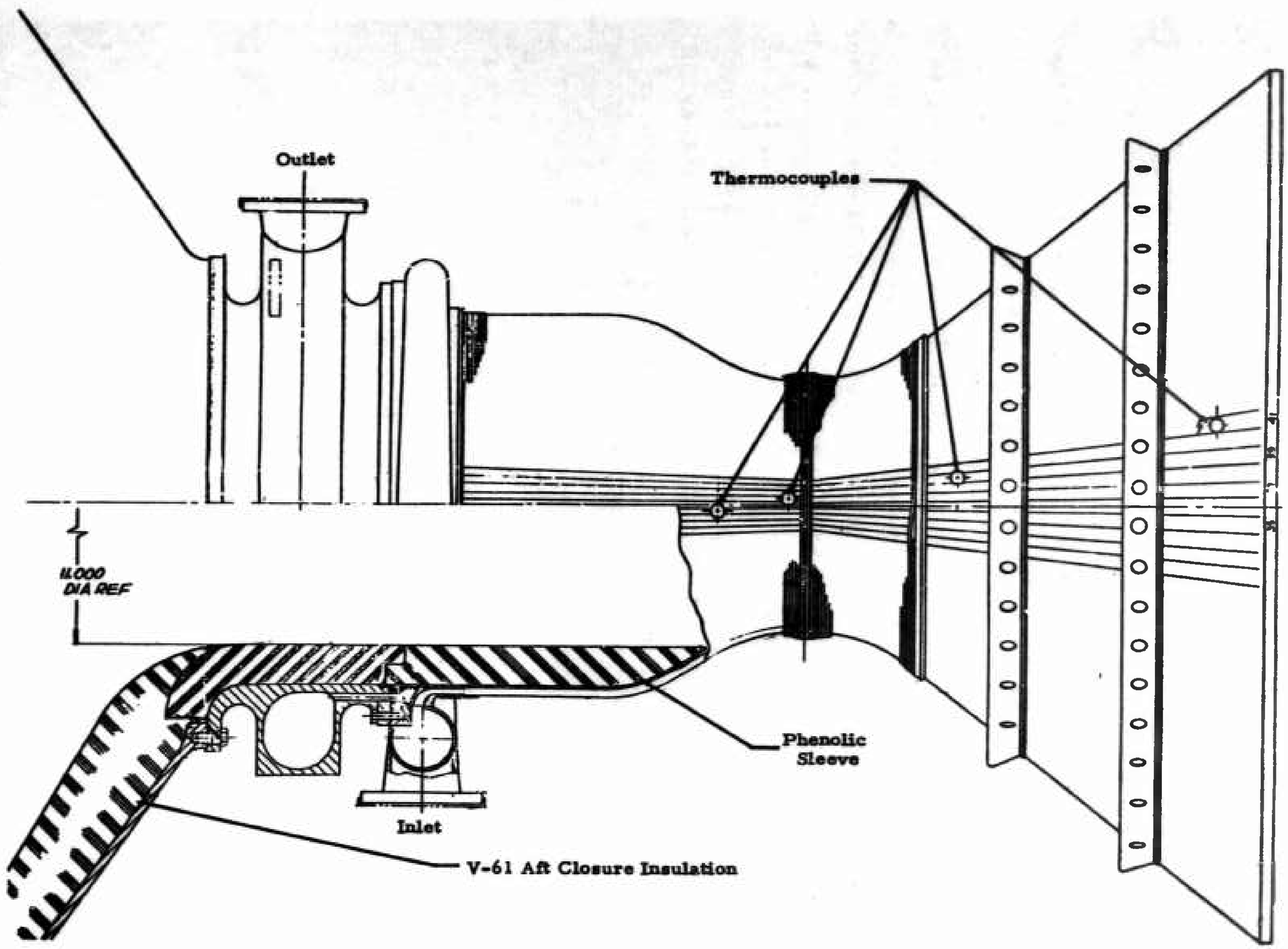


Figure 1. Nozzle Schematic View

# SECTION II

## GAS-PRESSURIZED COOLANT FACILITY DESCRIPTION

The water coolant system used for this series of test is located on Pad 1, Test Area 1-32 of the Air Force Rocket Propulsion Laboratory's solid test facility. The water coolant facility consists of a 2000-gal-capacity water tank pressurized by a 6000-psi gaseous nitrogen cascade. The entire system is capable of being pressurized to 1100 psi with a maximum flow rate of 1266 gal/min. Tank pressure can be regulated between $\pm 5$ psi with a modified Sky Valve regulator. Results of the flow tests and the previous firing have indicated that the instrumentation is calibrated to an accuracy which is within $\pm 4$ psi for pressure readings, and within $\pm 1^{\circ}F$ for temperatures. Flow rates from 600 to 1200 gal/min are easily obtainable and inlet pressure may be varied from 250 to 900 psi. Flow rates of the system are controlled by a motorized hand valve located in the downstream position.

Temperature instrumentation provided for support requirements are: water tank temperature, inlet and nozzle water temperature, and nozzle outlet water temperature. System pressures which may be recorded are: regulator pressure, tank pressure, and nozzle inlet pressure. Provisions have also been made in the data-acquisition system to record water pressure in the nozzle as well as flow rates. Momentum forces introduced in the nozzle from the high-pressure lines are reduced by using 4-inch flexible stainless steel pipe. A complete description of the water coolant facilities located at AFRPL may be obtained from Reference 1.

## SECTION III

## CHECKOUT TEST RESULTS

Checkout tests of the water-cooling and gas-pressurization systems were accomplished in accordance with procedures outlined in the Appendix. Checkout evaluation was completed four times prior to the third firing and the system was considered reliable and accurate.

Modulation of the water flow rate while the test was in progress was required. Upon ignition the following conditions were to be met:

| | |
|---|---|
| Water tank pressure | 1100 psig |
| Nozzle inlet pressure | 850 psig |
| Nozzle outlet pressure | 450 psig |
| Flow rate | 1200 gal/min |

At approximately T + 15 seconds into the firing it was desired to initiate reduction of the water flow rate by closing the downstream valve in steps while maintaining constant tank pressure. The anticipated final flow rate was 600 gal/min. The exact minimum flow rates to be attained and the practical size of the steps to be taken in reduction were determined by NASA and Aerojet-General Corporation prior to the firing. Instantaneous indication of water flow rates during the reduction maneuvers were obtained from a meter on the control console.

Prefire cold-flow checkout consisted of the following:

A. Leak check at tank pressures of 900 and 1100 psig, no flow.

B. Four runs with flow for 5 seconds at a tank pressure of 1100 psig and a flow rate of 1200 gal/min. The downstream valve was remotely closed until the water flow rate approached 900 gal/min and was maintained for 5 seconds. The downstream valve was then closed to allow water to flow at 600 gal/min. The purpose of these checkout runs was to confirm the ability of the system to modulate while flowing and to establish time intervals for closing the valve under pressure.

Table I shows the results obtained from the cold-flow checkouts prior to the third nozzle test.

TABLE I

| CHECKOUT OF WATER-FLOW RESULTS | | | | |
|---|---|---|---|---|
| TANK PRESSURE (psi) | PRESSURE IN (psi) | PRESSURE OUT (psi) | FLOW RATE (gpm) | TIME (sec) |
| 1080 | 1040 | 750 | 850 | 10 |
| 1080 | 760 | 320 | 1266 | 10 |
| 1080 | 810-1025 | 320-893 | 1295-610 | 10 |
| 1080 | 810-881-965-1040 | 320-548-760-930 | 1266-1085-845-560 | 10 |

## SECTION IV

## NOZZLE DESCRIPTION

### A. NOZZLE DESIGN

The nozzle fired on 17 February 1969 was a conventional Titan II, Second Stage regeneratively cooled nozzle modified with an external water-flow manifold adapter at the front end as shown in Figure 1. The adapter manifold incorporates a 0.332-inch-wide by 0.312-inch-deep groove around the feed-hole circle and permits uniform flow in all tubes. A two-piece silica carbon cloth phenolic sleeve was wrapped over the tubes in the throat entrance section (combustor region). The cooling requirement for the test was initially 1200 gal/min modulated to 600 gal/min at chamber pressure tailoff. Pressure drop across the nozzle was expected to be 300 psi at ignition and 150 psi near tailoff. Aft closure insulation was Gen-Gard V-61 a trowelable, air-cured, rubber insulation material. For the third nozzle test Aerojet-General evaluated the following conditions in areas of the nozzle exit section.

a. No coating with a grit-blasted substrate surface.

b. No coating with a smooth substrate surface.

c. A minimum of three ceramics whose melting temperature is greater than 4700°F. Consideration was given to the evaluation of $ZrO_2$, $SrO$-$ZrO_2$, and MgO.

$ZrO_2$, $HfO_2$ and $SrO$-$ZrO_2$ were selected for testing in the nozzle exit section. These materials have melting points of 4700°F or above and are easily plasma-arc-sprayed. Zirconia and hafnia have very low thermal conductivity and are known to have good thermal shock resistance when used as thin coatings. The Aerojet Company has had little experience with strontium zirconate and there is little published data other than that its thermal shock resistance is somewhat inferior to zirconia and other zirconates and its porosity is somewhat higher. When magesium oxide was eliminated because it proved impossible to plasma-arc-spray,

$SrO\text{-}ZrO_2$ was substituted due to its availability and ease of spraying.

MgO, $ZrO_2$, $HfO_2$ and $ThO_2$ are attractive due to their low thermal conductivity. There is no experience recorded concerning plasma-arc-spraying of thoria. This is probably due to its reported radioactivity and poor thermal shock properties. A special facility would be required for spraying thoria. MgO is reported to be difficult or impossible to plasma-spray due to its vaporization. This was confirmed by a laboratory test where 10 passes of the plasma torch over a substrate failed to result in a measurable increase in specimen thickness. The melting point of BeO at 4660°F is near the target of 4700°F, however, its thermal conductivity is high, it reacts with $H_2O$ above 3000°F and its reported toxicity creates unknown handling problems. The other candidate materials listed have melting points considerably lower than 4700°F and were eliminated from further consideration for that reason.

On the occasion of the NASA Project Manger's visit to the Aerojet Company on 22 January 1969, the possibility of testing the third nozzle at reduced water flow rates was discussed. This would be done by gradually reducing the water flow after approximately 10 seconds at full flow. By this time the start transient, which is characterized by high local heat fluxes due to the propellant grain pattern, will be past. The objective of reducing water flow is to demonstrate the effectiveness of the coating and the alumina($Al_2O_3$) plating in reducing heat to the coolant.

To establish the practicality of the above approach and determine the desired water flow reduction, it was necessary to perform the heat-transfer study that follows:

1. Method of Analysis

The water flow reduction can be accomplished by throttling the valve at the coolant outlet side of the chamber. As the flow is reduced the water pressure will increase in the chamber tubes. This increased pressure was considered in the analysis.

As part of the test program, this last nozzle has approximately 9.0 in. of bare, uncoated tubes at the aft end of the chamber to determine if alumina would plate out on these tubes; the previous test had alumina plating out on coated tubes in this region. A coolant bulk temperature rise of approximately 5°F was calculated because of the bare tubes and this increased temperature was also included for the start-transient analysis.

Two analyses were made for the coated chambers. The first assumed no alumina plating and the severe thermal conditions experienced during the start transients with coating temperatures of 3200°F. The second analysis assumed alumina plating at 3700°F and realistic coolant bulk temperatures experienced in the second test. In both, the water tank pressure was assumed to be 1100 psia and the water flow rate was reduced from 170 to 50 lbs/sec, or approximately 1225 to 360 gpm.

2. Discussion of Results

The maximum burnout heat-flux ratios and wall temperatures are shown in Figures 2 and 3. For the severe start conditions at full flow (170 lbs/sec) the $R_{BO}$ is 0.53 and the minimum flow for $R_{BO}$ of 1.0 is 70 lbs/sec or approximately 510 gal/min. Assuming the alumina plating does occur, the $R_{BO}$ at full flow (170 lbs/sec) is 0.39, and to achieve an $R_{BO}$ of 1.0, the water could be reduced to 50 lbs/sec. These results are valid only if the original coating remains intact.

3. Conclusions and Recommendations

1. Assuming the original coating does not spall, the water flow rate can be reduced to 80 lbs/sec without nozzle burnout.

2. It is recommended that the water flow be reduced in steps and held at each step for a minimum of 5 sec.

The basic coating that was used on Nozzle S/N 02 was applied except that no coating was applied over the aft 9.0 inches (measured axially) of the nozzle.

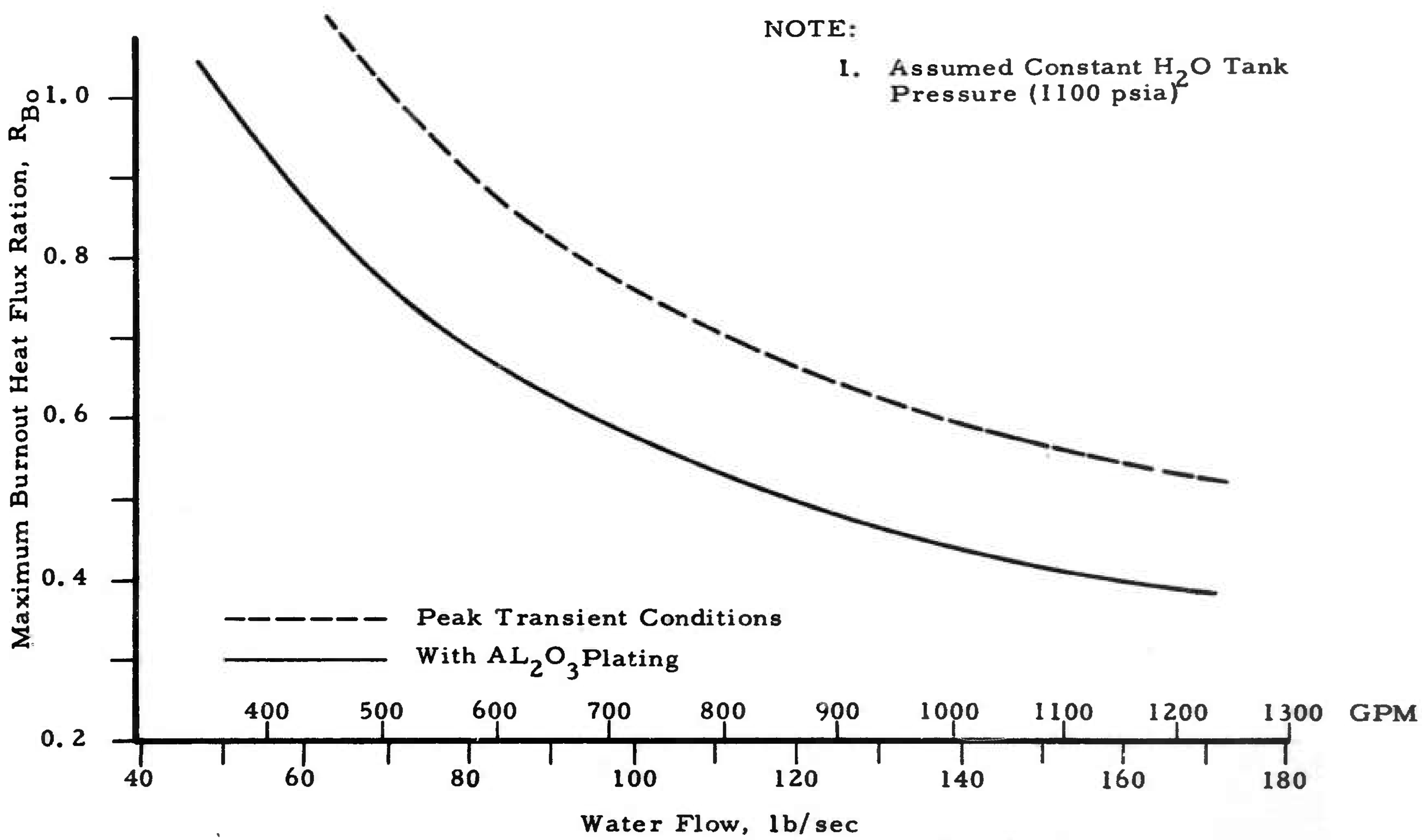


Figure 2. Coating Development Program, Effect of Coolant Flow Reduction.

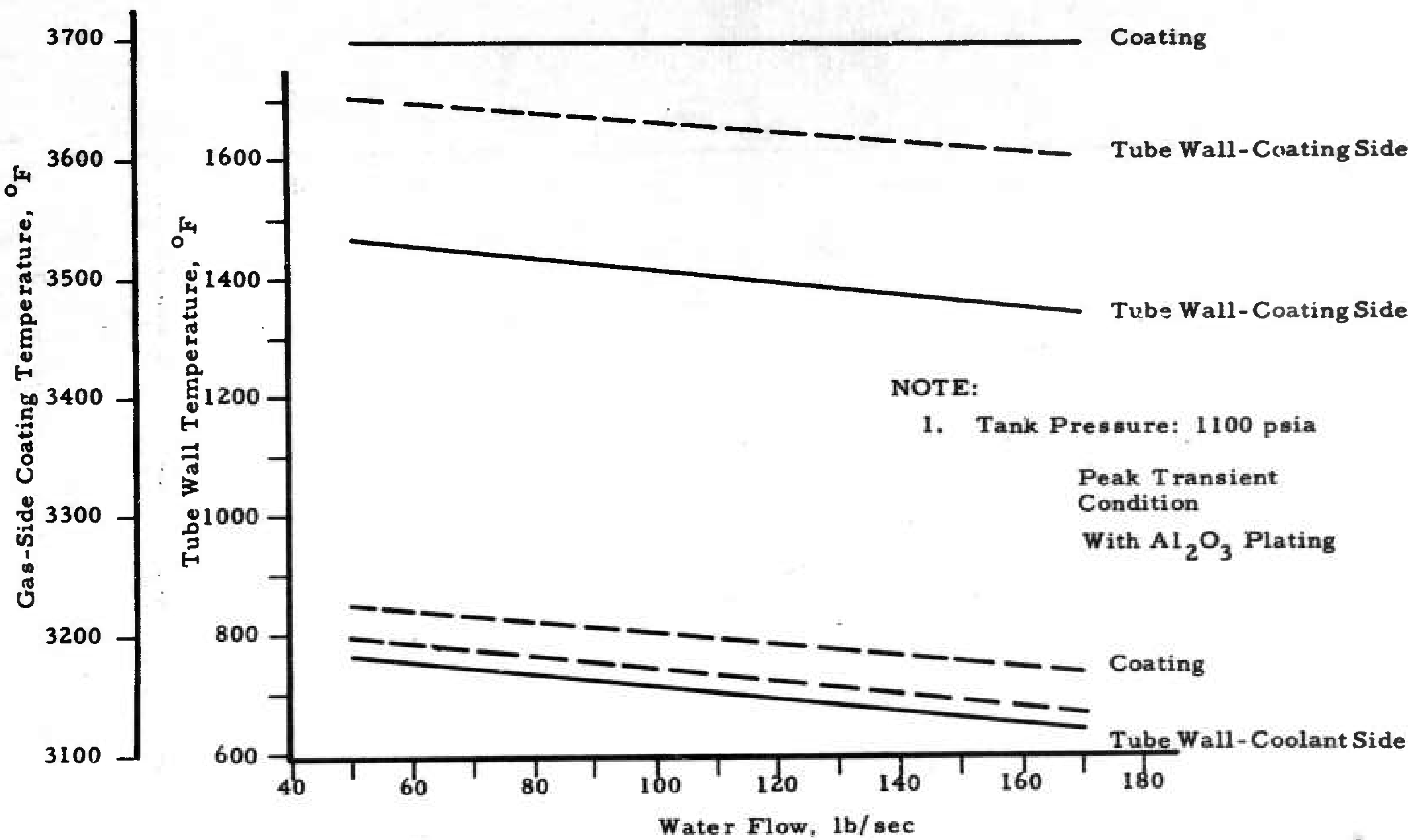


Figure 3. Cooling Development Program, Wall Temperatures.

The experimental coatings were applied between the axial stations according to the following schedule (Figure 4):

| Station No. | Coating |
|---|---|
| 0-7 | Bare |
| 7-9 | Bare - Grit-Blasted |
| 9-11 | $HfO_2$ |
| 11.1 - 13.0 | SrO $ZrO_2$ |
| 13.1 - 14.9 | $ZrO_2$ |
| 10-11 | W |
| 12-12.9 | W |
| 14-14.8 | W |

The initial plasma-arc-spraying of W at Station 10 was attempted at usual spraying parameters. The coating colored dark blue, indicating excessive heating. Spraying was stopped after three or four revolutions. After reducing power input by half and doubling surface speed, spraying was continued with satisfactory results.

The ablative inserts and adapter were assembled with the nozzle and pressure checked at 1000 psig with water. A leak was found at the base of one of the thermocouple tubes. This was repared, and retesting indicated no leakage. Since thermocouples were not required for this test, the tubes were plugged with swagelock fittings. The nozzle was crated and shipped to AFRPL on 28 January(2).

## B. MOTOR INSTALLATION

The nozzle and aft closure were attached to a 2nd Stage Wing I Minuteman motor and were then placed on Pad 1, Area 1-32 at the AFRPL. Flow checks, thermocouple calibration, and instrumentation checks were made prior to firing. Figure 5 shows the installation of the nozzle and the motor. During cold-flow runs on the test pad, two thermocouples were found to be inoperative on the inlet and outlet stations of the nozzle.

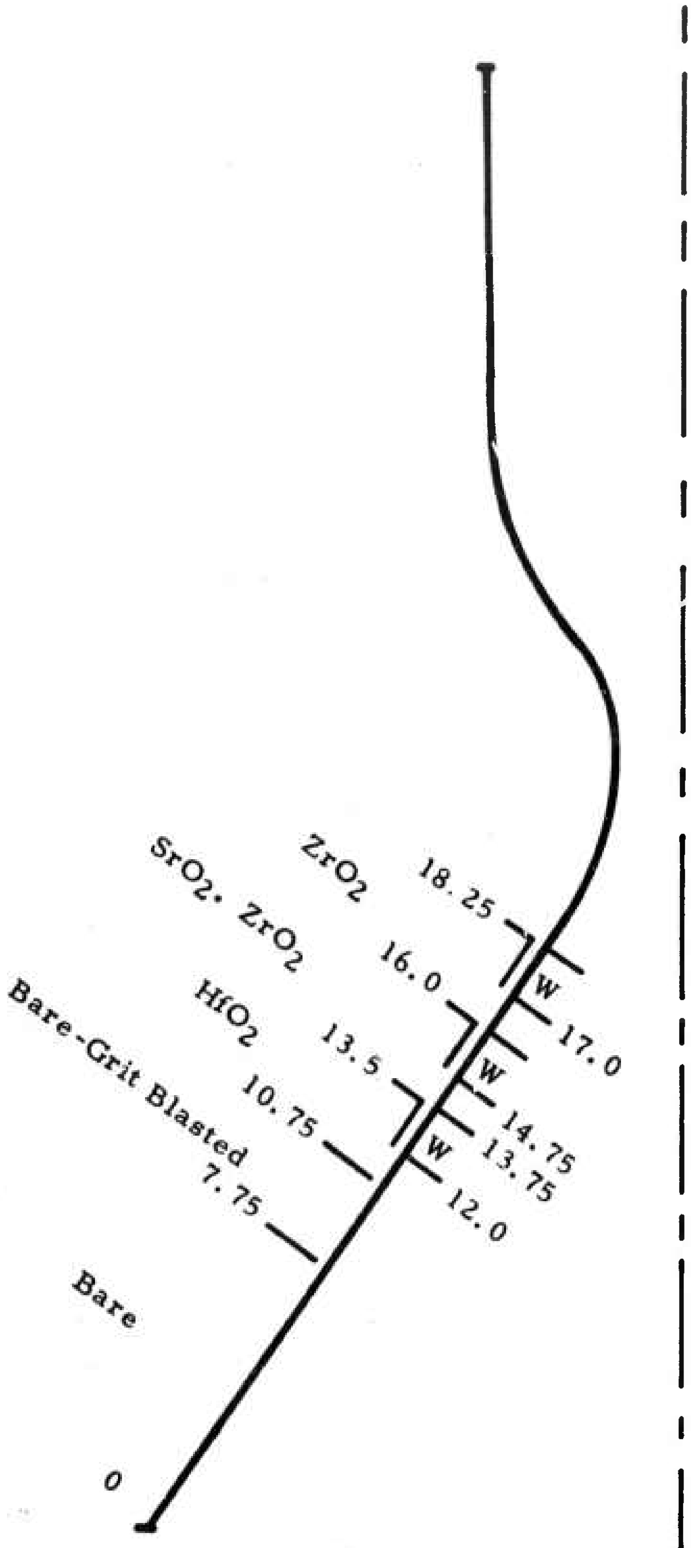


**Figure 4. Coating Location**

Faulty welds were determined to be the cause of malfunctions, and were not rewelded or replaced because the remaining thermocouples were considered adequate for temperature recording. Prefire nozzle photos showing the $Al_2O_3$ base coatings are presented in Figures 5 through 7. Nozzle instrumentation specifications are shown in Table II.

## TABLE II. NOZZLE INSTRUMENTATION CHECKLIST

| INSTRUMENTATION SPECIFICATION SHEET | | | | TEST NUMBER | | PROJECT TITLE | Proj. 305903AMG NOMAD, $H_2O$ COOLED NOZZLE | | DATE 30-1-69 |
|---|---|---|---|---|---|---|---|---|---|
| ITEM NO | PARAMETER | LOCATION | TRANSDUCER TYPE | TRANSDUCER RANGE | CALIBRATION RANGE | FREQUENCY RESPONSE | RECORDING SYSTEM | CHANNEL | REMARKS |
| 26/F | IA Thrust | Fwd Closure | Bridge-Resist. Type | 0-50000# | 0-50000# | 50 CPS | DigOSC | 20 | Gain Setting - 28.3 |
| 27/FI | B " | " | " | " | " | " | Dig | 22 | " " " |
| 28/PC | -1 Press. | " | " | 0-1000psig | 0-1000psig | " | meter Dig osc | 24 | " " " |
| 29/PC | -2 " | " | " | " | " | " | Dig | 26 | " " " |
| 30/PC | I-3 " | Coolant In. | " | " | " | " | | 28 | " " " |
| 31/PC | O-4 " | Coolant Out | " | " | " | " | meter Dig osc | 30 | " " " |
| 32/PW | T-5 " | Water Tank | " | " | " | " | " | 32 | " " " |
| 33/PO | R-6 " | Reg. Press. | " | " | " | " | " | 34 | " " " |
| 34/LP | -1Position | Coolant OUt | Linear Pot | 0-100% | 0-100% | " | meter Dig | 0 | |
| 35/CW | -1Vol Flow | Cool Flow | Turbine Type | GPM 101.12-1266.21 | 25-315cps | " | Dig OSC | 1 | |
| 9/TC | CI-9 Temp | Coolant In 1 | Cu/C | -300°F to 750°F | 0° to 250°F | 3cps | Dig | 37 | Gain Setting -10.0 |
| 10/TC | CI-10 " | 2 | " | " | " | " | " | 39 | " " " |
| 11/TC | CI-11 " | 3 | " | " | " | " | " | 40 | " " " |
| 12/TC | CI-12 " | 4 | " | " | " | " | " | 41 | " " " |
| 13/TC | CI-13 " | 5 | " | " | " | " | " | 42 | " " " |
| 14/TC | CI-14 " | Coolant Out6 | " | " | " | " | " | 43 | " " " |
| 15/TC | CI-15 " | 7 | " | " | " | " | " | 44 | " " " |
| 16/TC | CI-16 " | 8 | " | " | " | " | " | 45 | " " " |
| 17/TC | CI-17 " | 9 | " | " | " | " | " | 46 | " " " |
| 18/TC | CI-18 " | 10 | " | " | " | " | " | 47 | " " " |
| 19/TC | CI-19 " | $H_2O$ Tank | " | " | -50 to 150°F | " | " | 48 | " " " |
| X-1 | Ign Pulse | | Critical Event | | | | Dig OSC | C-1 | |
| X-2 | 0.5 pps timing | | Normal Event | | | | Dig | N-30 | |
| X-3 | 0.05pps timing | | " | | | | " | N-31 | |
| X-4 | 0.0125 pps timing | | " | | | | " | N-32 | |
| X-5 | 2 pps timing | | " | | | | OSC | | |
| X-6 | 10 pps timing | | " | | | | OSC | 2 | |
| 36/P7 | Pres noz. | in Nozzle | Bridge Resist Type | 0-1000psig | 0-1000psig | 50cps | OSC | | |
| 37/P8 | " " | out Nozzle | " | 0-1000psig | 0-1000psig | 50cps | OSC | | |
| | | | | | | | | | |
| | | | | | | | | | |

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## TABLE II. NOZZLE INSTRUMENTATION CHECKLIST (Continued)

**INSTRUMENTATION SPECIFICATION SHEET**

| TEST NUMBER | PROJECT TITLE | DATE |
|---|---|---|
| | Proj. 305803AMG<br>NOMAD $H_2O$ COOLED NOZZLE | 30-1-69 |

| ITEM NR | PARAMETER | LOCATION | TRANSDUCER TYPE | TRANSDUCER RANGE | CALIBRATION RANGE | FREQUENCY RESPONSE | RECORDING SYSTEM | CHANNEL | REMARKS |
|---|---|---|---|---|---|---|---|---|---|
| | 1. Flowmeter converter pulse and flowmeter outputs shall be recorded on oscillograph. | | | | | | | | |
| | 2. The nozzle inlet and outlet pressures will be used only for flow tests check-outs. | | | | | | | | |
| | APPROVED: | | | | APPROVED: | | | | |
| | | DAVID ZORICH, 2Lt. USAF<br>Project Engineer | | | | TULLY BECKER<br>Project Instrumentation Engineer | | | |

RPL Form 24A

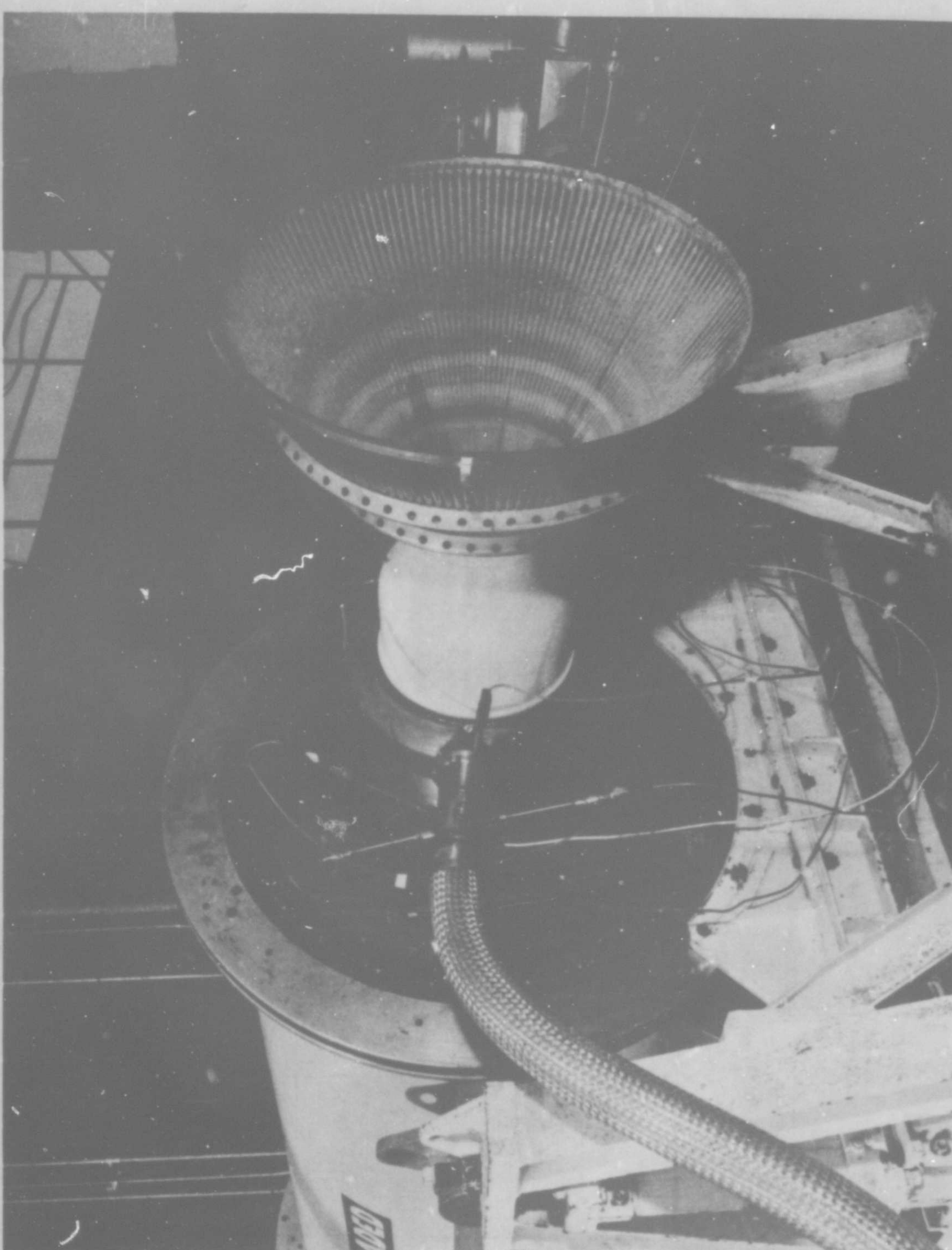

Figure 5. Nozzle Installation Showing Thermocouple Installation (Prefire).
(Motorized Water Flow Valve in Background)

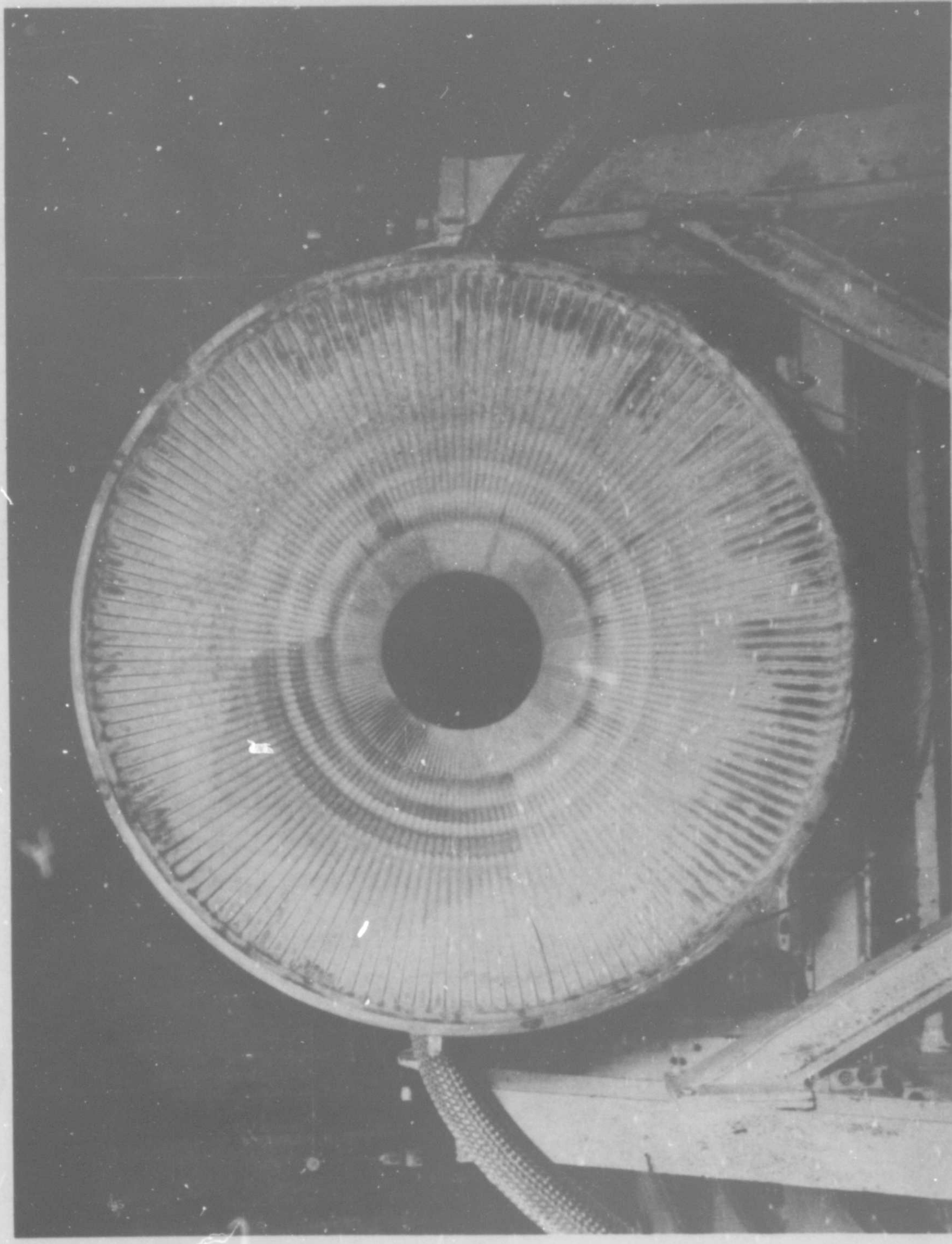

Figure 6. Prefire Exit Cone Showing Coating Locations.

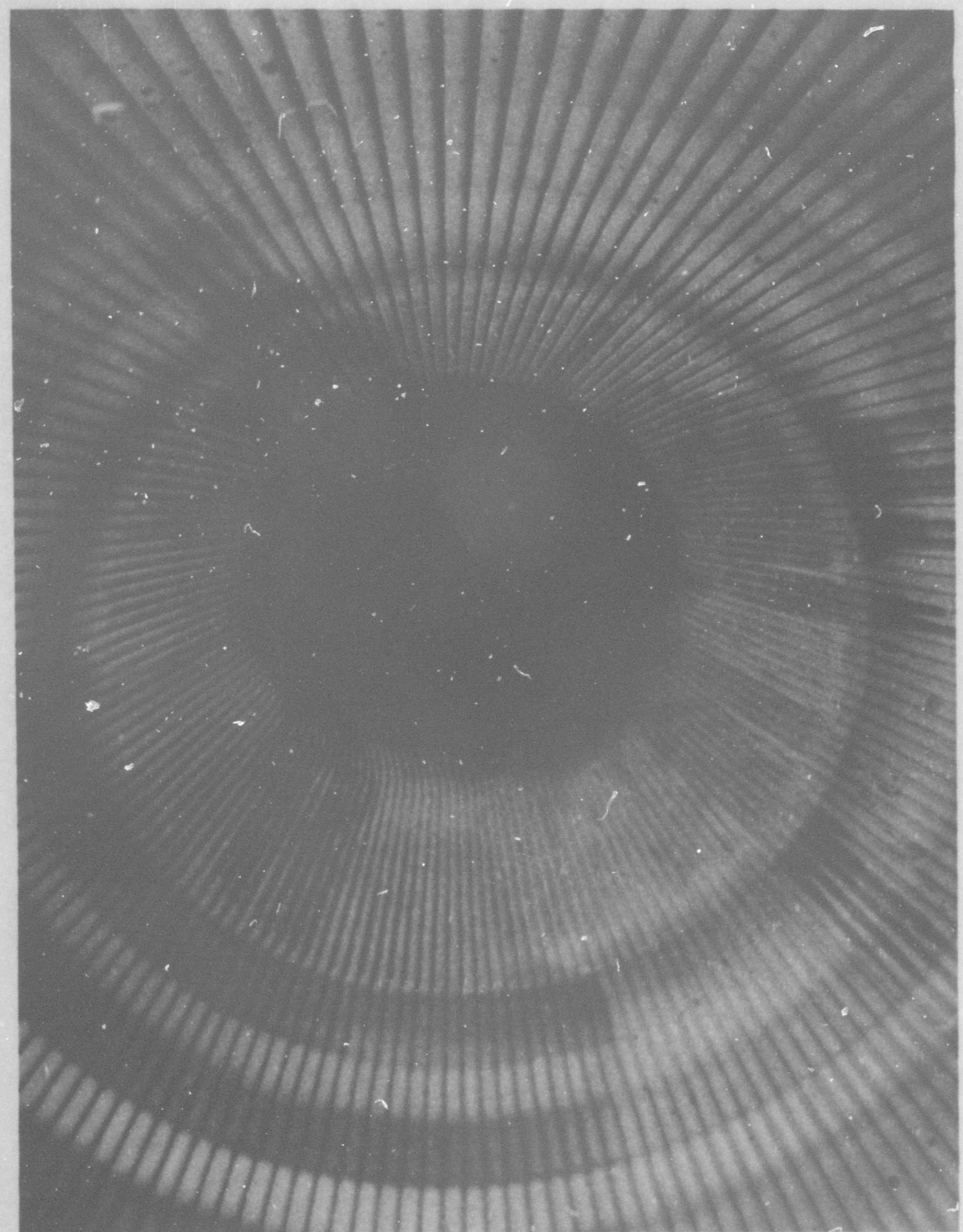

Figure 7. Close-Up of Nozzle Throat Showing Coating Gradations (Prefire)

## SECTION V

## TEST FIRINGS AND RESULTS

Test firing was conducted on 19 February 1969 at the AFRPL. Test duration was 63 seconds and average chamber pressure was 380 psi. Theoretical flame temperature was 5700°F and the water-flow conditions were 1200 gal/min and 800-psi nozzle inlet pressure at ignition and 600 gal/min and 500-psi inlet pressure at tailoff. Postfire examination of the nozzle indicated that no tubes burned through and no film boiling occurred. Flow rate was modulated throughout the firing as was the inlet pressure (Figure 8). After the completion of the firing, the water was allowed to flow at pressure for 7 seconds and the remaining water in the water tank was gradually run through the nozzle in order to minimize heat soak through the nozzle tubes. Reexamination of the nozzle indicated that an extensive layer of $Al_2O_3$ from the solid propellant (approximately 1/4-inch thick) had deposited on the exit cone of the nozzle. This is shown in Figure 9. Samples of this material were subjected to metallurgical, X-ray diffraction and chemical analysis.

The alumina deposit appeared to have been liquid on the surface and flow patterns are shown in Figure 10. Upon cooldown, the solidified $Al_2O_3$ contracted and pulled away from the nozzle tubes. Postfire photos are shown in Figures 11 and 12. A piece of alumina taken from this aft section was examined by X-ray diffraction. The analysis indicated only alpha $Al_2O_3$ was present. Spectrographic analysis indicated that no other elements of atomic weight greater than 20 were present other than aluminum.

The tapered ablative liner showed no excessive erosion and no alumina buildup between the ablative liner and the nozzle coolant tubes, as was encountered in nozzle firing No. 1. In addition, pieces of the $Al_2O_3$ were sectioned, mounted, and polished for metallographic examination.

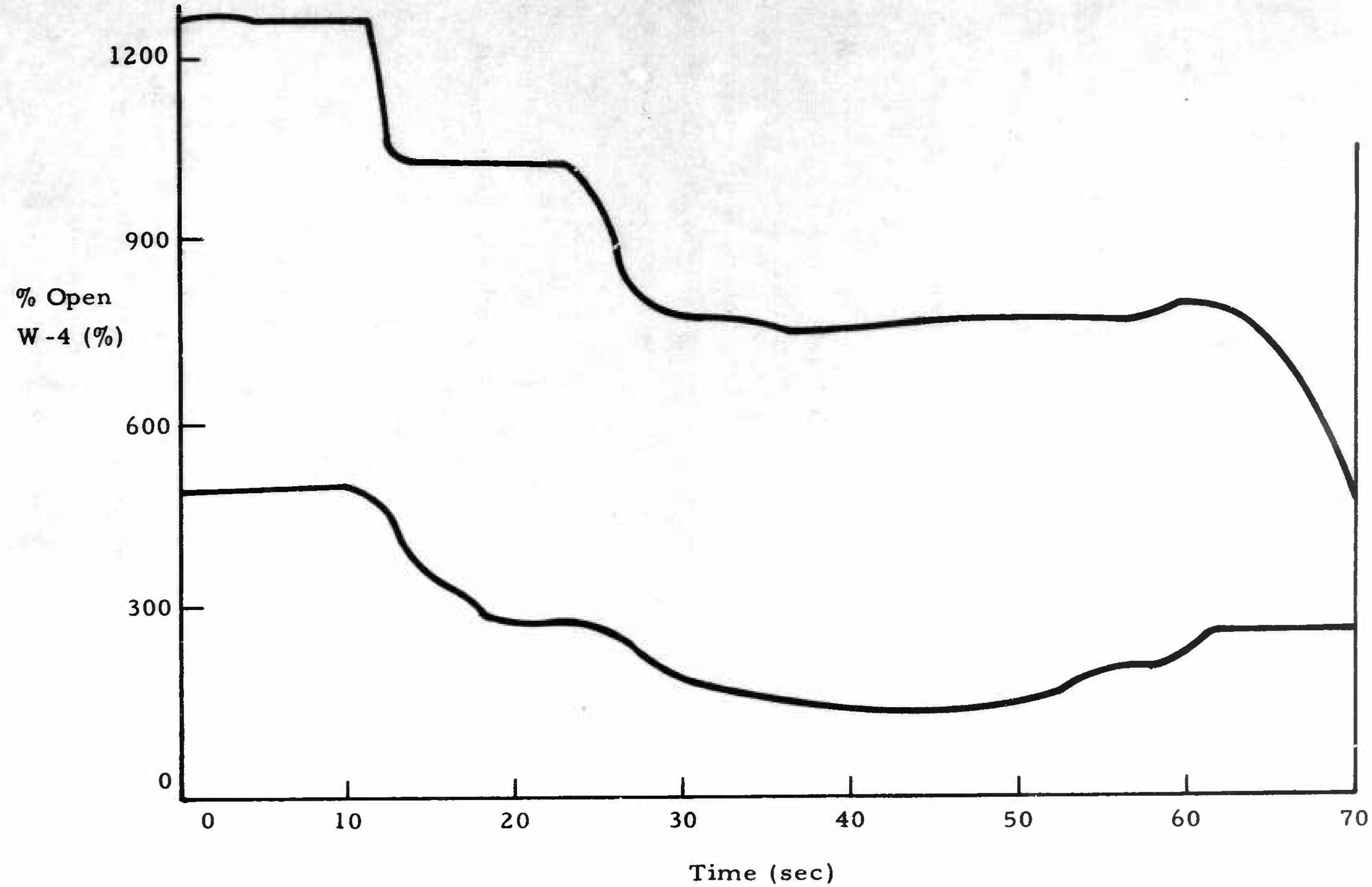


Figure 8. Water Flow Rate and Percent Open W-4 versus Time.

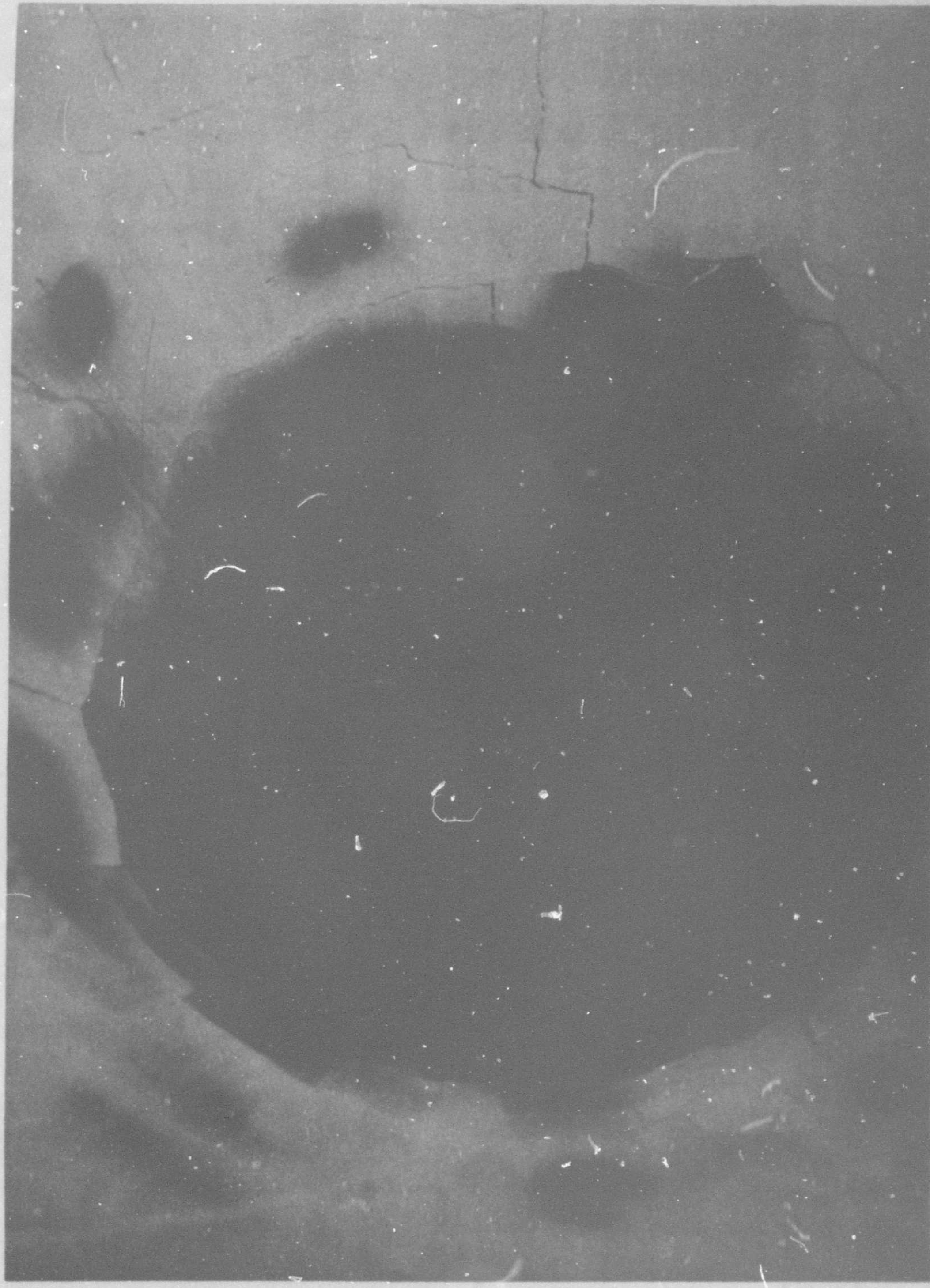

Figure 9. Postfire Throat Region Showing Alumina Buildup.

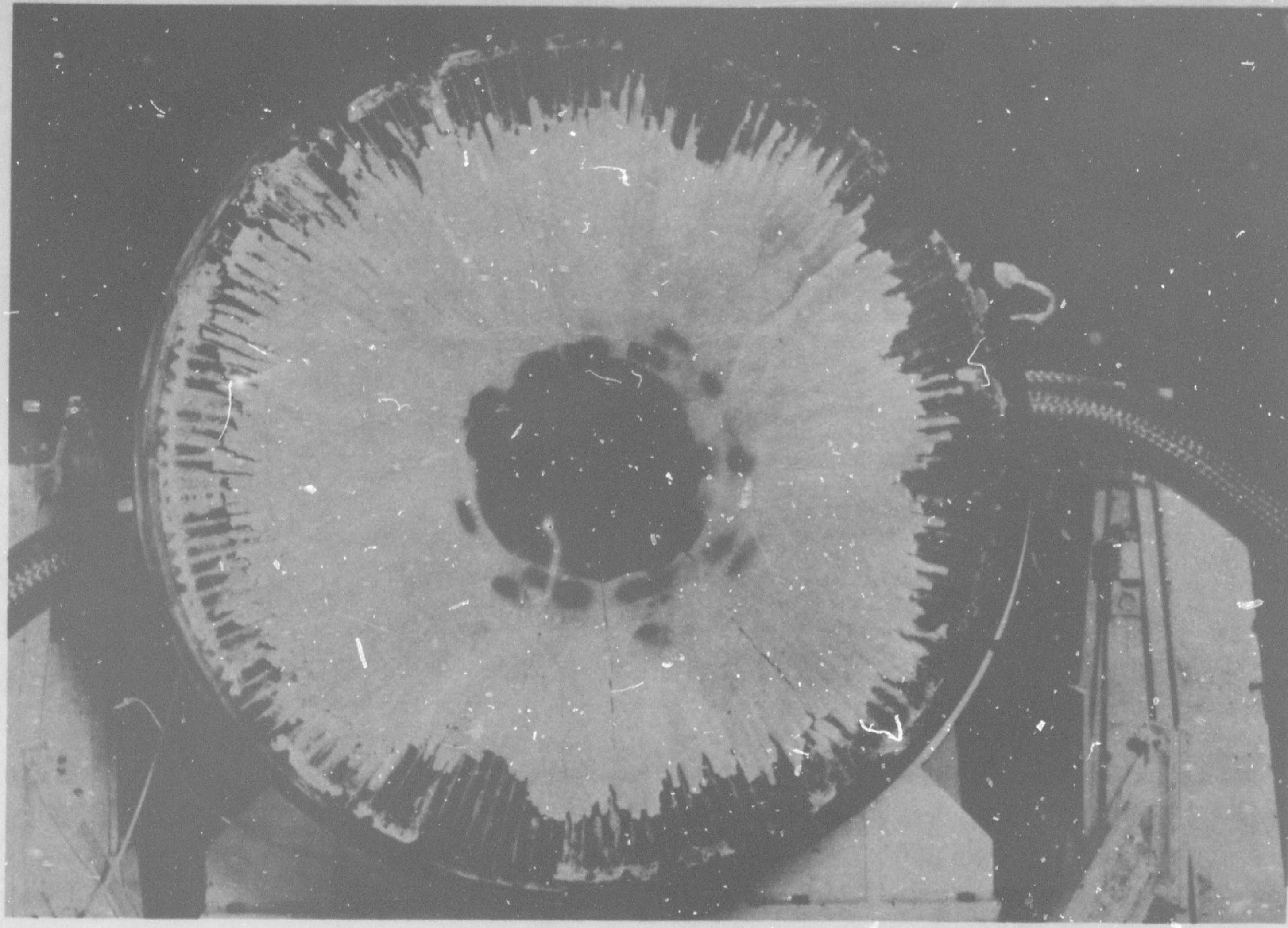

Figure 10. Postfire Exit Cone Showing Alumina Buildup.

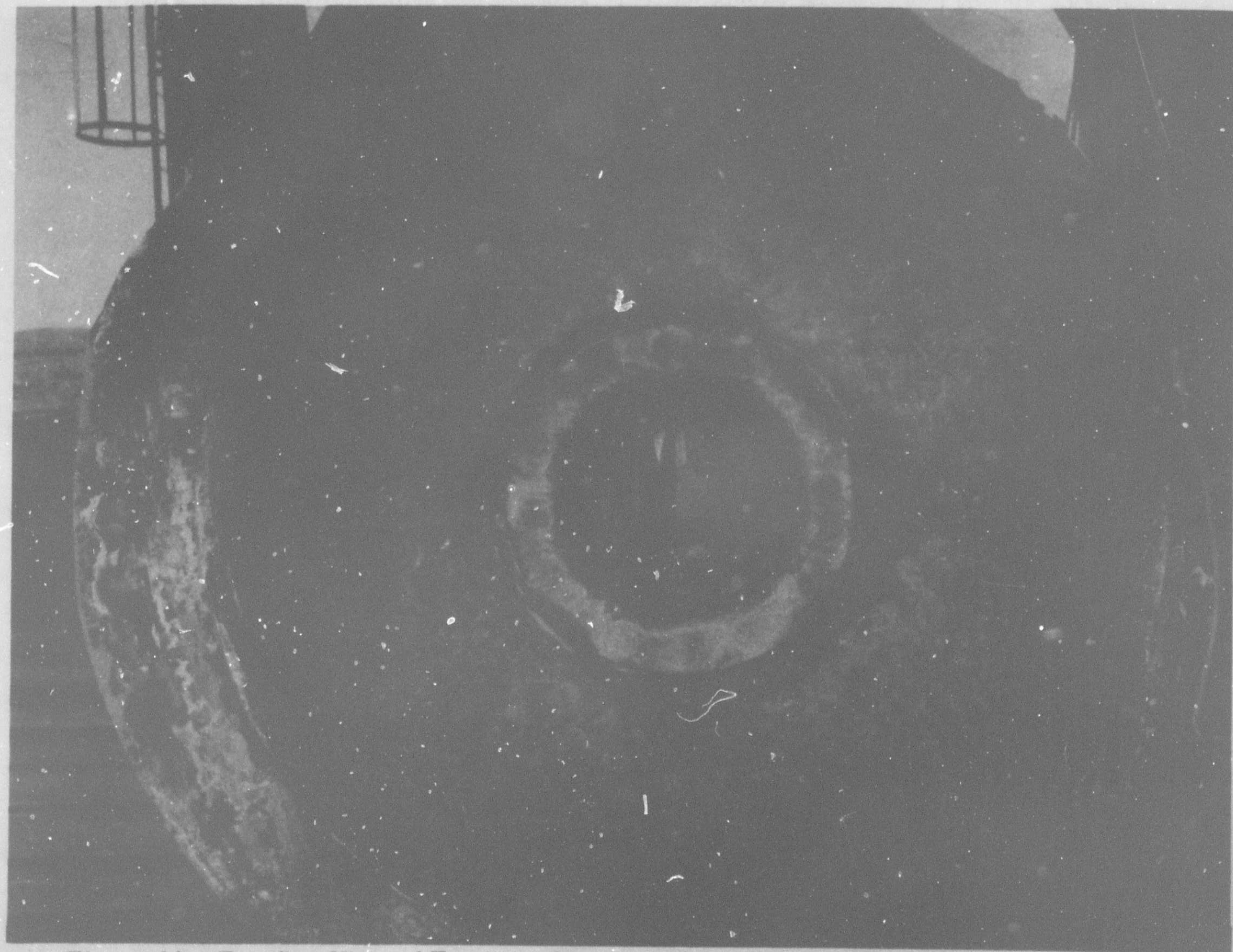

Figure 11. Postfire View of Entrance Section and Aft Closure Showing Erosion Patterns.

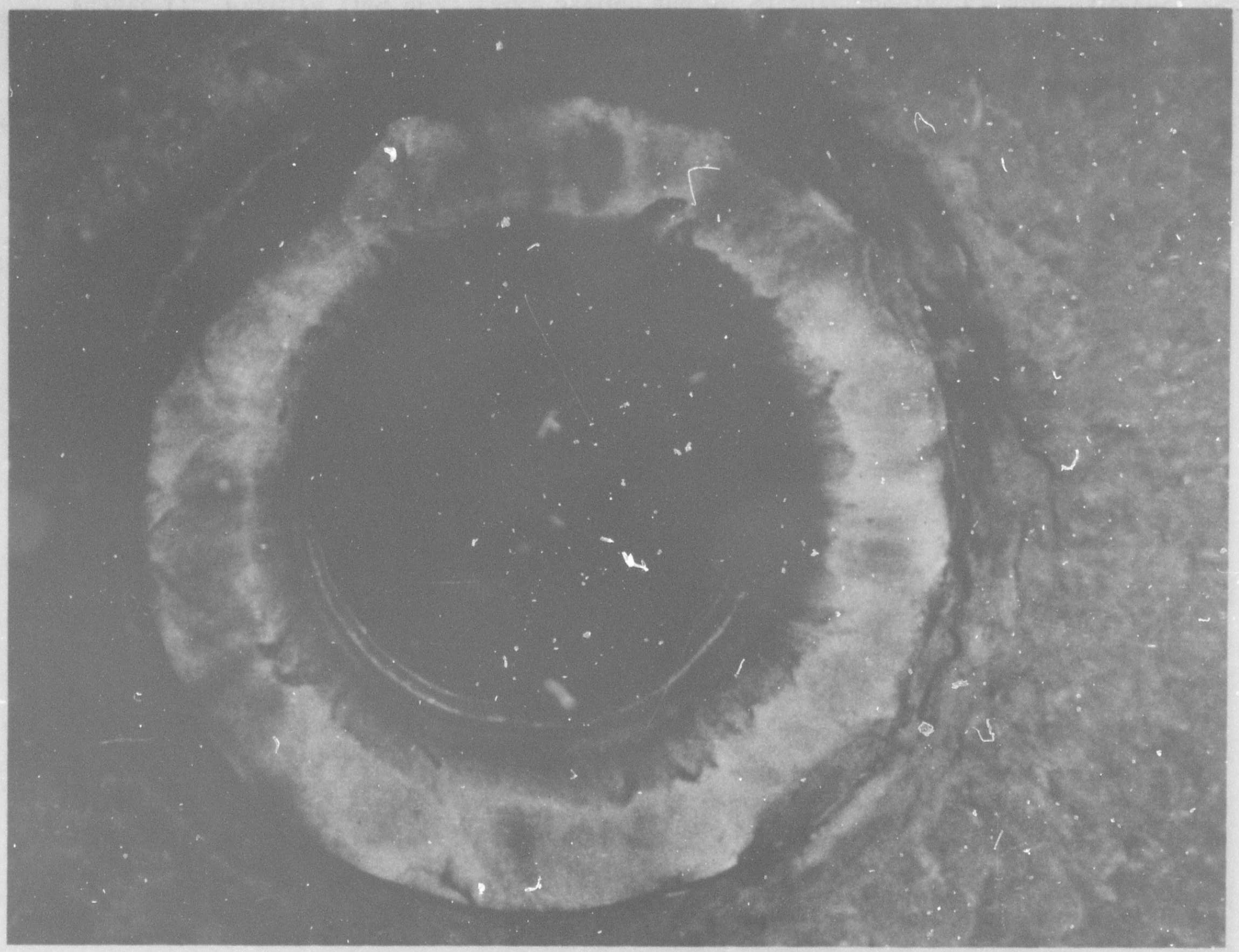

Figure 12. Postfire Close-Up Showing Ablative Sleeve Erosion and Nozzle Throat.

The exhaust $Al_2O_3$ evidently plated out on the relatively cold tube walls and valleys (3100°F) during the first few seconds of firing, then when the thickness of the deposit was such that the hot side exceeded 3630°F, the $Al_2O_3$ became molten and sluffed off while remaining semi-molten underneath. Then as $P_c$ dropped off and the heat flux decreased, the molten and semi-molten layer solidified, and as further cooling occurred, this area was apparently again covered with the same type of random grain deposit indicated in the layer near the tube (3).

The coolant temperatures recorded during the firing are shown in Figures 13 and 14. Water tank pressures, regulator pressures and nozzle inlet and outlet pressures are shown in Figure 15. It should be noted that the water tank pressure and regulator pressures show a substantial decrease. This was due to a relay failure which caused the water tank regulator to vent off $GN_2$. Nozzle inlet pressure was maximized during this non-pressurization phase by closing the downstream valve.

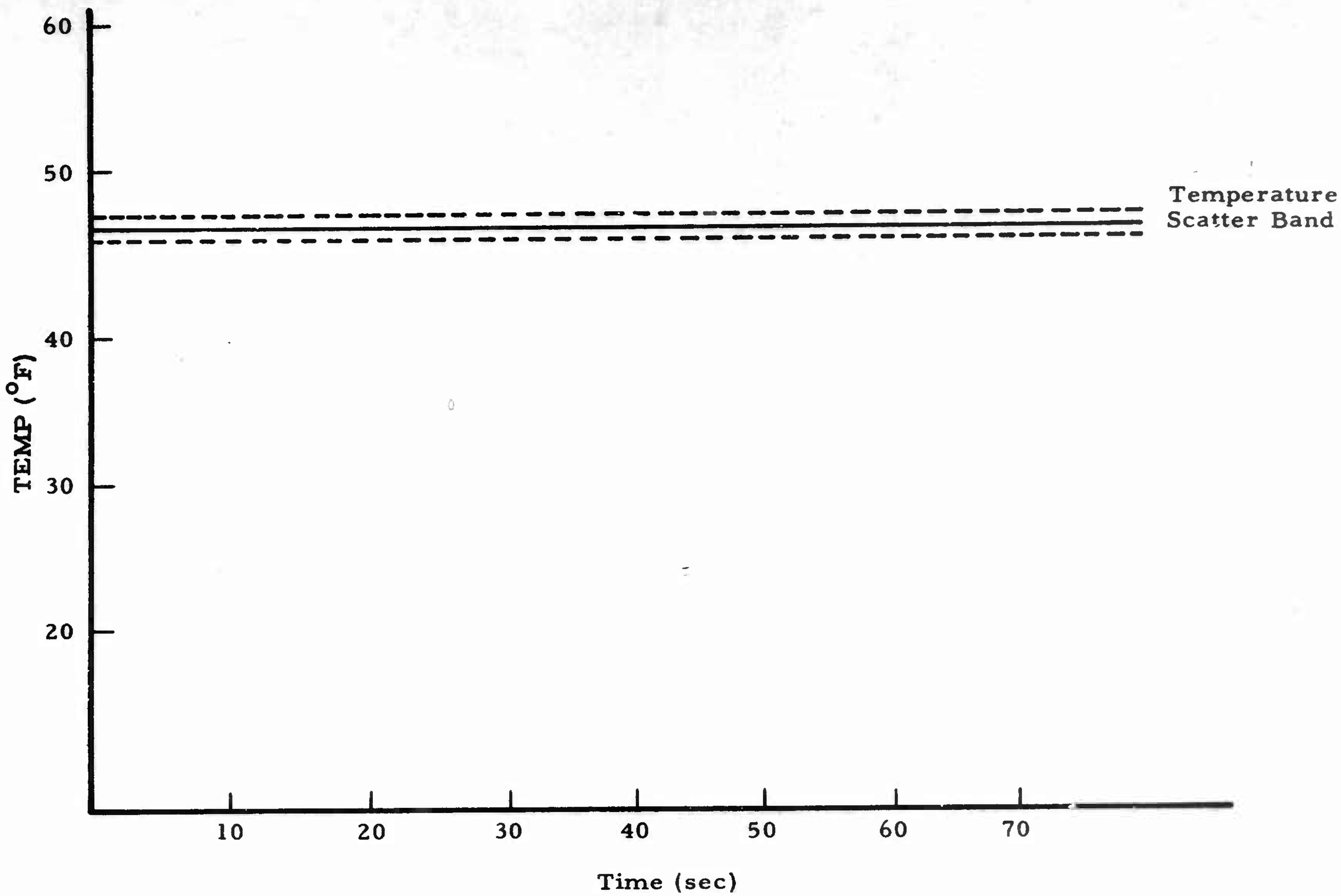


Figure 13. Coolant Inlet Temperature versus Time.

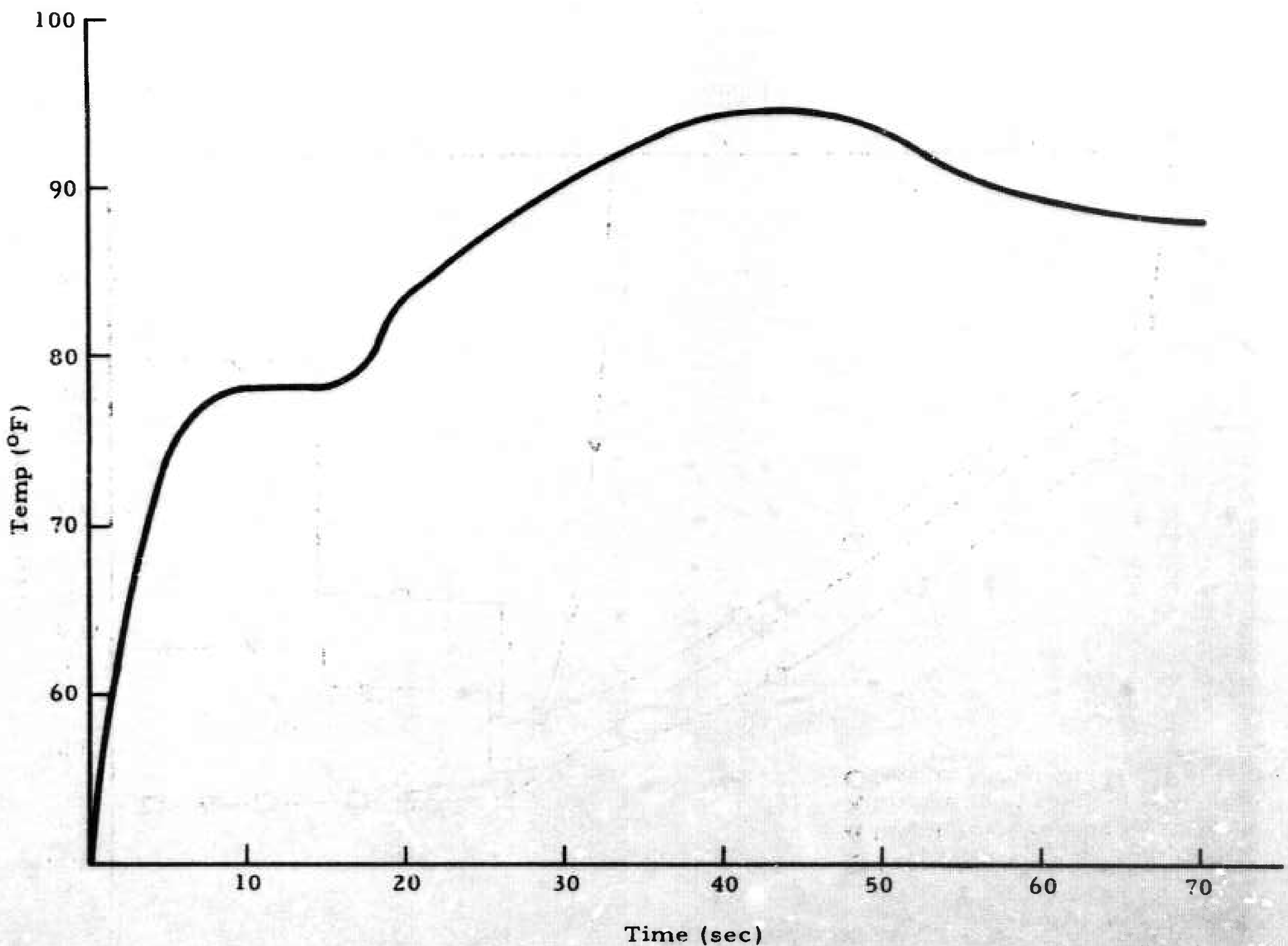


Figure 14. Coolant Outlet Temperature versus Time.

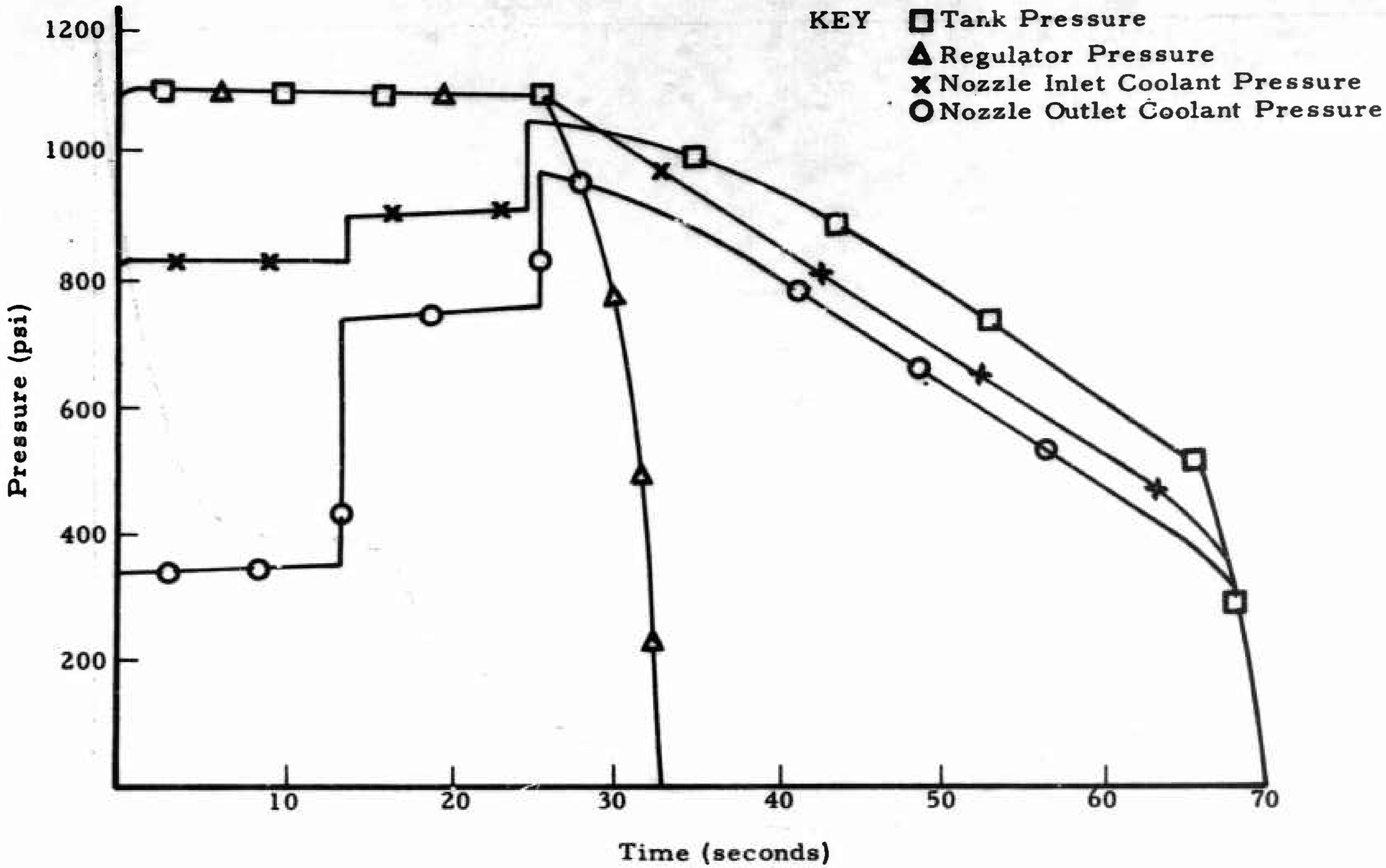


Figure 15. System Pressures versus Time.

## SECTION VI

## CONCLUSIONS

1. The feasibility of using a water-cooled nozzle on a large solid propellant motor was proven with the successful test firing described in this report. No indication of burnthrough or film boiling was indicated.

2. The operation of the gas-pressurized water-flow system was proven successful at tank pressure of 1100 psi. A maximum flow rate of 1350 gal/min was demonstrated with an inlet pressure of 825 psi.

3. The use of alumina base coatings on nozzle components will effectively reduce the heat flux induced upon the nozzle walls.

4. The heat-transfer analysis (with appropriate margins of safety) was adequate, and was substantiated in that lower coolant flow rates were successfully used.

## REFERENCES


1. Zorich, D.R. and Bassoni, A.A., "Description of a Gas-Pressurized Water Flow System for the NASA Water-Cooled Nozzle Program", AFRPL-TR-68-163, AD 843201, September 1968.

2. Stubbs, V.R., Personal Communication, 31 January 1969.

3. Zorich, D.R. and Bassoni, A.A., "Demonstration Test Firing of a Water-Cooled Nozzle on a Solid Propellant Motor", AFRPL-TR-69-35, February 1969.

# APPENDIX

# CHECKOUT PROCEDURES

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## APPENDIX

## CHECKOUT PROCEDURES

The gas-pressurized water coolant system for the NASA water-cooled nozzle is composed of a pressurized 311-$ft^3$ $GN_2$ vessel rated at 6000 psi and a 2017-gallon water tank with a working pressure of 750 psi.

The checkout procedure consisted of four steps:

1. STEP 1 wherein the $GN_2$ vessel and associated fittings were pressurized incrementally to 500, 1,000, 3,000, and 6,000 psi. The system checked for leakage.

2. In STEP 2 the entire water system was incrementally pressurized to 900 psi with leakage and vibrational failures noted and repaired.

3. In STEP 3 the 60-second operational tests were performed to determine which method of flow-rate control (pressure changes versus controllable valve) were satisfactory for actual operation.

4. In STEP 4, full-scale dry run, based on data from the operational tests, was used to acquaint all personnel with final firing procedures.

Test and instrumentation crew personnel were responsible for locating and repairing leaks, locating vibrational instabilities and insuring that remote valves and instrumentation were in proper working order. During high-pressure checkouts (4000 and 6000 psi) test personnel were not permitted to enter the pad area until 1 minute after specified test conditions had been established and maintained. During checkout procedures "B," test instrumentation was operative.

In the event that leaks were located at connections, the project engineer decided whether venting of any or all of the system was required prior to repair operations. Leaks in pipes, valves, or pressure vessels were to terminate the checkout, and venting was mandatory. Once repairs were completed, the project engineer was to reestablish the checkout conditions existing at the time of interruption and to proceed with the tests. All other decisions relating to emergency situations during the checkout sequence were to be made by the Pad Foreman.

A. Checkout of Water System

After water and gas systems were completed, the entire system was checked out as follows:

1. Check all hand valves to make sure that they open and close freely.

2. Check all remote valves remotely, make certain that valve and light and meter sequence are correct as follows:

| VALVE DESIGNATION | CONTROL | NORMAL CONTROL CONDITION | | INDICATOR (COLOR) |
|---|---|---|---|---|
| G-3 | $H_20$ Tank Vent | Open | | Green |
| W-3 | $H_20$ Nozzle In | Closed | | Green |
| W-4 | $H_20$ Throttle Valve | Open | | Meter |
| W-5 | $H_20$ Nozzle Out | Closed | | Green |
| | Regulator Open | Closed | | Green |
| | Regulator Press | Open | -MOM- | Green |
| | Regulator Vent | Closed | -MOM- | Green |
| | Regulator Rapid Vent | Closed | -MOM- | Green |

-MOM- Momentary

3. Fill water tank with tap water as follows:

   a. Make certain $H_2O$ tank vent valve G-4 is open.

   b. Fill $H_2O$ tank through hand valve W-1.

NOTE: Record time it takes to fill $H_2O$ tank.

4. Gravity Flow Check.

   a. Make certain $H_2O$ tank vent valve G-4 is open.

   b. Open $H_2O$ hand valve W-2.

   c. Open $H_2O$ nozzle in Valve W-3 (light should be red).

   d. Open $H_2O$ throttle valve W-4 (light should be red).

   e. Open $H_2O$ nozzle out valve W-5 (light should be red).

Allow water to flow for 10 seconds or until all air has been removed from the lines.

   f. Close $H_2O$ nozzle out valve W-5 (light should be green).

   g. Close $H_2O$ nozzle in valve W-3 (light should be green).

NOTE: Leave hand valve W-2 and throttle W-4 open.

5. $GN_2$ Vessel Pressurization:

   a. Make certain $H_2O$ tank vent valve (G-3) is open.

   b. Open $GN_2$ hand valve (G-2).

   c. Set regulator to zero dome pressure.

   d. Charge $GN_2$ vessel incrementally as follows: 500, 1,000, 3,000, and 6,000 psi.

   e. Check all connections and plumbing leading to or from $GN_2$ vessel with "Leak Tech" or soap. If repairs are needed, notify project engineer before proceeding.

6. Flow Integrity Tests:

NOTE: Use Operational Test Procedure "A".

Checkout Test No. 1

Pressurize $H_20$ tank pressure to 250 psi. Do checkout steps 1 to 10.

Checkout Test No. 2

Pressurize $H_20$ tank pressure to 500 psi. Do checkout steps 1 to 10.

Checkout Test No. 3

Pressurize $H_20$ tank pressure to 750 psi. Do checkout steps 1 to 10.

Checkout Test No. 4

Pressurize $H_20$ tank pressure to 900 psi. Do checkout steps 1 to 10.

7. Sixty-Second Operational Tests:

NOTE: For these operational tests, use Procedure 2 and make certain that instrumentation is operative:

Checkout Test No. 1

NOTE: During this test, the tank pressure will be varied in order to determine flow-rate characteristics.

a. Fill water tank with tap water. Follow Step No. 3.
b. Make certain $GN_2$ vessel is charged to 6000 psi.
c. Pressurize $H_20$ tank to 750.
d. Do checkout steps 1-11 (except allow water to flow for 60 sec).

Checkout Test No. 2

NOTE: During this test, valve W-4 (throttle valve) will be opened to the following positions:

(1) Full open
(2) 1/4 Open
(3) 1/2 Closed
(4) 1/4 Open
(5) Full Open

a. Fill tank with tap water. Follow Step No. 3.
b. Make certain $GN_2$ vessel is charged to 6000 psi.
c. Pressurize $H_20$ tank to 750 psi.
d. Do checkout steps 1-11 (except allow water to flow for 60 sec.)

8. Full-scale Dry Run.

B. OPERATIONAL TEST PROCEDURES "A"

1. Make certain that valves:

   G-3 - - $H_2O$ tank vent valve, and

   W-1 - - $H_2O$ tank fill valve, are closed.

2. Note: $H_2O$ throttling valve will not be used during the flow integrity tests. Leave in normal open position.

3. Set dome pressure on regulator and pressurize $H_2O$ tank to specified test pressure with remote $GN_2$ regulation controls.

4. Open $H_2O$ nozzle inlet valve W-3 (red light).

5. Make general visual check of waterlines, $GN_2$ lines, connections, and valves.

6. Open $H_2O$ nozzle out valve W-5 (red light) before, during, and after test. Allow water to flow for 10 seconds.

7. Open $H_2O$ tank vent valve G-4 (green light)

8. Close $H_2O$ nozzle outlet valve W-5 (green light).

9. Close $H_2O$ nozzle inlet valve W-3 (green light).

C. OPERATIONAL TEST PROCEDURES "B"

1. Make certain that valves:

   G-3 - - $H_2O$ tank press valve,

   G-4 - - $H_2O$ tank vent valve,

   W-1 - - $H_2O$ tank fill valve, are closed.

2. Note: Make certain throttle valve W-4 is in open position before starting test.

3. Jet regulator dome pressure and pressurize $H_2O$ tank to specified test pressure with remote $GN_2$ regulator controls.

4. Open remote $H_2O$ inlet valve W-3 (red light).

5. Make general visual check of waterlines, $GN_2$ lines, connections, and valves before, during and after test.

6. Notify - console to start firing sequence: At T-5 sec., open $H_2O$ nozzle out valve W-5 (red light). Allow water to flow for 60 seconds.

7. Open $H_2O$ tank vent valve G-4 (green light).

8. Close $H_2O$ nozzle outlet valve W-5 (green light).

9. Close $H_2O$ nozzle inlet valve W-3 (green light).

10. Stop all instrumentation and make a visual check of nozzle tubes for cracks in nozzle coatings.

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13. ABSTRACT

The objective of this test program was to evaluate the feasibility of using a water-cooled nozzle on large solid propellant motors. The coolant requirement for this test was 1200 gal/min water flow rate with an inlet coolant pressure of 850 psi. The flow was reduced during the test with a minimum water flow rate of 560 gal/min. The nozzle performed successfully with no indication of tube burnthrough or film boiling occuring. Test duration was 62 seconds at an average chamber pressure of 380 psi. Results of this test indicated the entire system operated satisfactorily at maximum operating conditions.

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| 14. KEY WORDS | LINK A | | LINK B | | LINK C | |
|---|---|---|---|---|---|---|
| | ROLE | WT | ROLE | WT | ROLE | WT |
| Plamsa-Sprayed Coatings | | | | | | |
| Water-Cooled Nozzle | | | | | | |
| 260-inch motor | | | | | | |
| Refractory oxides | | | | | | |